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Optical Turbulence Measurements During One Morning and Two Evening Transition Periods in a Desert Basin

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C_n^2 data recorded at 4, 8, 16, and 32 m heights over a desert basin during three test periods of about two hours each near sunrise or sunset were analyzed. C_n^2 between 4 and 8 m was found to be relatively constant. C_n^2 at 8, 16, and 32 m were least-squares fit to $C_n^2 = (C_n^2)_0\ (z/z_0)^m$ over 5 and 15 minute averaging periods.

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OPTICAL TURBULENCE MEASUREMENTS DURING ONE MORNING AND TWO EVENING TRANSITION PERIODS IN A DESERT BASIN

INTRODUCTION

Propagation of a laser beam through a turbulent atmosphere results in an angular divergence beyond that associated with diffraction. The key parameter that describes the optical turbulence is the refractive index structure parameter C_n^2 based on the 2/3 law structure function:

$$C_n^2 = < (n_1 - n_2)^2 > / r_{12}^{2/3} , \tag{1}$$

where n_1 and n_2 are the refractive index at points 1 and 2, r_{12} is the distance between those two points, and the angle brackets represent the ensemble average. The 2/3 law [1, 2] is valid in the inertial subrange in which the energy spectrum has a -5/3 power dependence on the inverse of the fluctuation scale size. The inertial subrange exists for Reynolds numbers of 10^5 or greater and is bounded by the fluctuation scale sizes l_0, below which inhomogeneities are rapidly dissipated by viscous forces, and L_0, which is close to the largest possible scale size. l_0 is typically a few millimeters, and L_0 is about 0.35 (the von Karman constant) of the altitude z under the conditions described here. Wyngaard [1] provides a general discussion of surface-layer turbulence; Tatarskii [2] contains a more complete description.

The C_n^2 measurements were made on the White Sands Missile Range in New Mexico. The behavior of C_n^2 in a New Mexico desert basin has been previously reported by Kunkel and Walters [3, 4] and Kunkel, Walters, and Ely [5]. Reference 3 describes a diurnal model and compares the model to experimental data. The agreement is good for the daytime but is less satisfactory at night and during the transition periods near sunrise and sunset. Reference 4 reports C_n^2 behavior under nighttime (very stable) conditions and Ref. 5 deals with both daytime and nighttime conditions.

The C_n^2 measurements in this report were made during the transition periods in support of laser beam propagation tests described in a separate report [6]. The propagation tests addressed the effect of turbulence on the propagation of diffraction-limited beams. The magnitude of the effect is related to the ratio of the transmitter aperture diameter to the lateral coherence length r_0, which in turn depends on the integral of C_n^2 along the propagation path with a spherical divergence factor that weights the path near the transmitter. In Eq. (2), k is the wavenumber ($2\pi/\lambda$), r is the distance from the transmitter, and R is the distance between the transmitter and the receiver. Lateral coherence length, discussed in Ref. 7, is based on pioneering work [8, 9]. This report fits the data to a power law to obtain an expression for $C_n^2(r)$ so that r_0 can be calculated for the laser beam propagation tests [6, 10]. The C_n^2 measurements fit to the power law were recorded at only two or three heights at a single location near the transmitter, but the path weighting in Eq. (2) and time averaging makes the power law useful for calculating r_0 for our tests.

$$r_o = 1.68 \left[k^2 \int_0^R C_n^2(r) \, (1 - r/R)^{5/3} \, dr \right]^{-3/5} \tag{2}$$

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EXPERIMENT DESCRIPTION

The experimental site was located in the Tularosa Basin of southern New Mexico. The area within 5 km of the site is flat and sparsely covered with low brush. Table 1 lists the three test periods, which are named after their sequential Julian days (i.e., the 289th and 290th days of the year). The first period, 289AM, began nearly one hour after sunrise (7:05), and the evening test periods ended about the time of sunset (18:26). Thus, the test periods were expected to include the time at which C_n^2 goes through its diurnal minima. Reference 3 has shown that the minima in a desert basin occur 1 to 1.5 h after sunrise and 0.5 to 1.0 h before sunset. Air-surface temperature differences and solar radiation went through or to zero during the 289AM and PM test periods. During 290PM, the solar radiation dropped to zero, but the air-temperature difference passed through zero about 0.5 h before the test period began. Figure 1 (redrawn from Ref. 11) shows the diurnal cycles.

Table 1 — Test Period Description

Test Period	Date	Time (LST)	Mean Wind Speed (m/s)* at 3-m height
289AM	10/16/79	7:52-9:45	1.8
289PM	10/16/79	16:24-18:51	3.0
290PM	10/17/79	17:07-18:45	1.1

*Meters per second

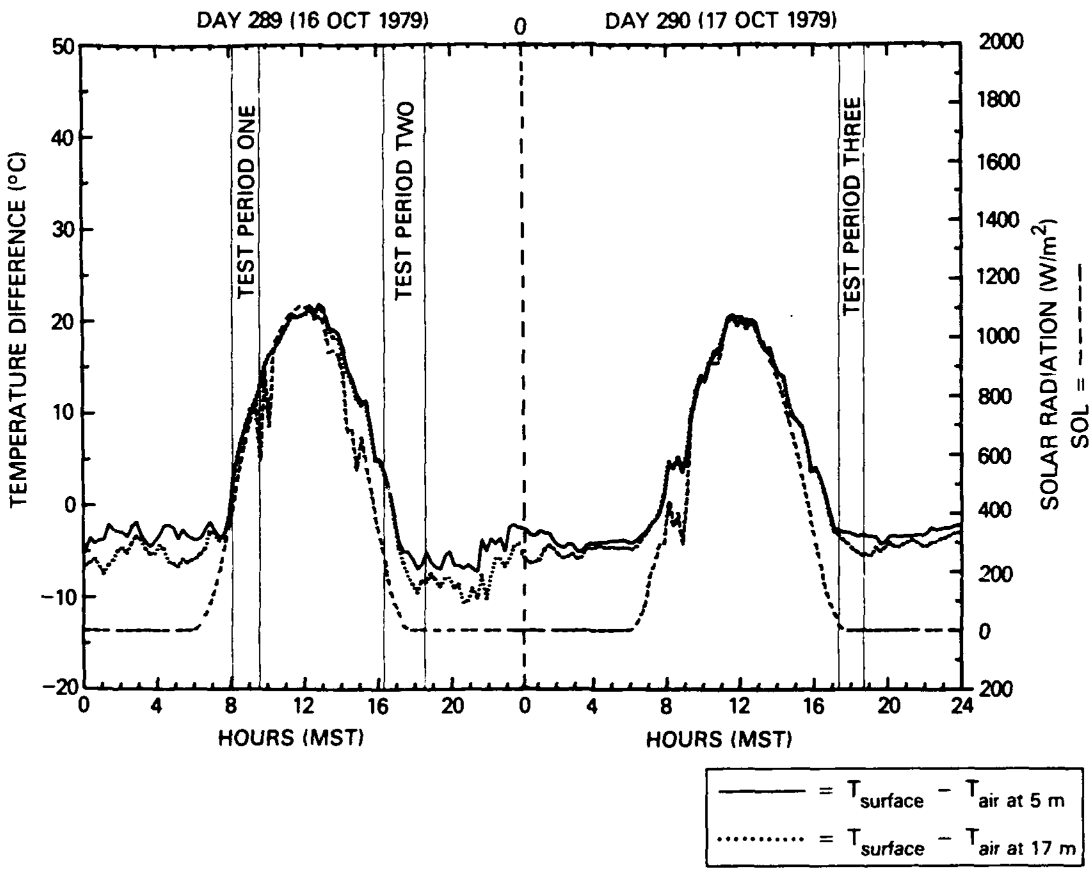

Fig. 1 — Differences between surface and air temperatures and solar radiation over the two test days. Redrawn from Ref. 11.

For the given wind speeds of 1.1 m/s or greater, the Reynolds number at 3-m height is 10^5 or greater. Therefore, the 2/3 structure law for C_n^2 (Eq. (1)) is valid. The optical refractive index fluctuations, furthermore, are most likely caused by temperature fluctuations because both the water vapor content (4 torr) and the soil moisture content are very low.

To scale C_n^2 with height requires atmospheric boundary layer information. The layer of interest is the free convective layer that extends from the surface layer, which is dominated by wind shear, to about one-tenth the height of the lowest inversion. Figure 2 of Kaimal et al. [12] shows the diurnal variation of an inversion base for a flat site in Minnesota One hour after sunrise, the base was only 100 to 200 m above the ground and then rose to several km by early afternoon. An hour before sunset, the convective boundary layer dissolution occurred abruptly and propagated from the top down. For the purpose of discussion we assume that the inversion base behavior at our site was qualitatively similar to that reported for the Minnesota site.

C_n^2 was measured at heights of 4, 8, 16, and 32 m with the exception of 290PM when the 16-m sensor was inoperable. According to the work of Kaimal et al. [12], the 32-m recordings and possibly the 16-m recordings as well may be in the mixed layer above the free convection layer during 289AM. The rapid dissolution of the layers in the evening transition periods contributes an uncertainty about the conditions under which our measurements were made.

The optical scintillometers used to measure C_n^2 were located near a laser transmitter that was situated on a small knoll such that the center of the laser aperture was about 8 m above the desert basin. The laser transmitter was directed to the west to a receiver 10.5 km away and 80 m higher than the transmitter. The receiver directly overlooked the desert basin and was set on a foothill of the San Andres mountain range.

Each scintillometer consisted of an incoherent light source and a receiver ,ith two apertures (5-cm dia.) separated by 13.5 cm [4,13]. In these experiments, the source and receiver were separated by 250 m. C_n^2 determined from intensity fluctuations is applicable to wavelengths from the visible to the infrared because n-1 is a weak function of wavelength. For example, only a 2% difference exists between n-1 at 0.5 mm and n-1 at 3.8 mm [14]. The sensors were sampled at 1 Hz and averaged over 10 s. Figure 2 displays the entire data set for 289PM. Occasional noise spikes are apparent and were traced to individual points with anomalously high C_n^2. These points (33 out of 6600) were replaced by averages of the surrounding points. This step later proved to be unnecessary, because the results were not significantly affected.

C_T^2 was measured by Airborne Research Associates of Weston, MA on a flight near the end of the 290PM period. They used 4.5-μm diameter tungsten resistance thermometers located on a wingtip at a separation of 0.85 m. The C_T^2 values were converted to C_n^2 as described in Ref. 5. Figure 3 shows the data recorded from 18:38:03 to 18:40:26 along with scintillometer sensor data recorded from 18:38:00 to 18:40:30.

RESULTS AND DISCUSSION

The time period over which the data are averaged should be long enough to sample large scale fluctuations and short enough to avoid drift in the mean value of C_n^2. The scale size associated with the largest fluctuations is approximately equal to the height; at 32 m height, about eight of these fluctuations will be present in the 250-m path at any time. Sampling over only 1 min can result in sampling two additional fluctuations for a wind speed of 1 m/s along the optical axis of the scintillometer. During the transition periods, model results [3] indicate that the mean C_n^2 will change by a factor of about two in 5 to 10 min in a desert basin with an assumed wind speed

of between 1 and 4 m/s. Averaging periods of 5 and 15 min were selected as a compromise between adequate sampling of low-frequency fluctuations and drift in the mean C_n^2.

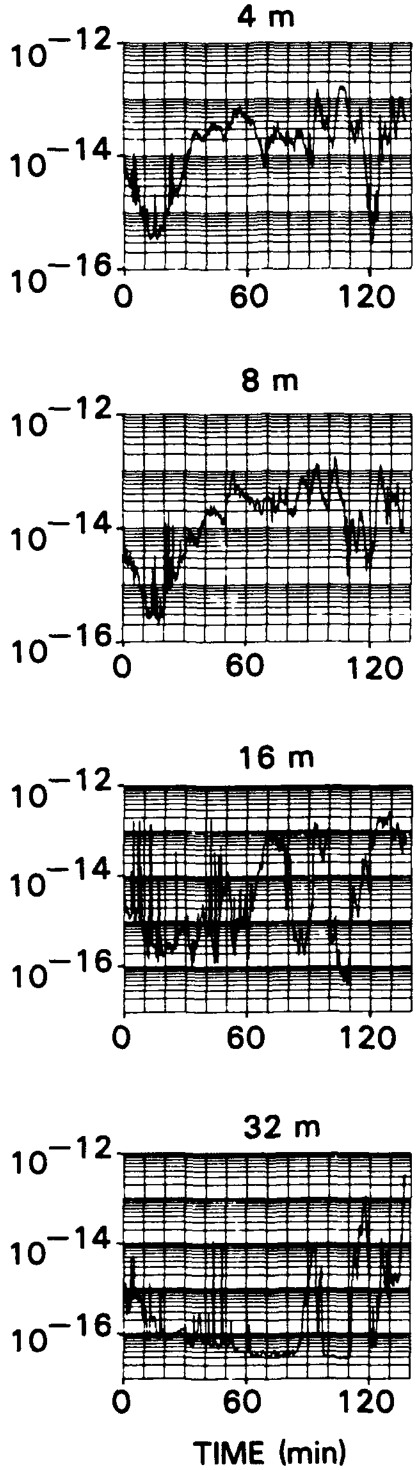

Fig. 2 — C_n^2 data in units of $m^{-2/3}$ recorded during test period 289PM at 4 heights on a common pair of towers

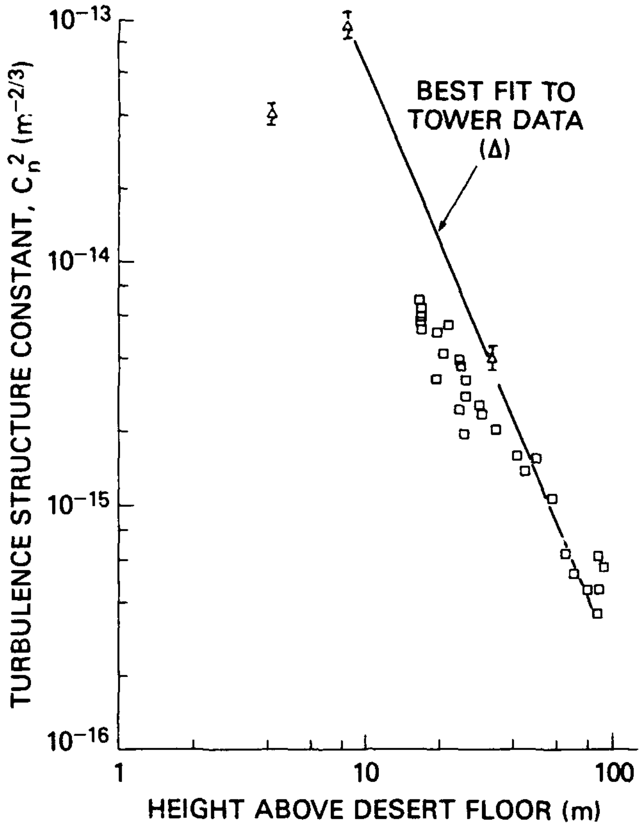

Fig. 3 — C_n^2 recorded simultaneously by the scintillometer sensors (Δ) and by the microthermal sensor mounted on an airplane (□) during 290PM test period

Figures 4, 5, and 6 display the 5-min averaged log C_n^2 data and standard deviation for each test period. Throughout this report, log-based statistics are used. The average C_n^2 is 10 raised to the power of the average log C_n^2, and the standard deviation is 10 to the power of log σ (σ represents the standard deviation for an individual log C_n^2 datapoint).

During the 289AM period, C_n^2 at each height increased slowly with the exception of C_n^2(8 m) at the beginning of the period. A rapid increase was expected then because the C_n^2 minima occur at about this time after sunrise [3]. Further into the test period, a fixed ratio develops between C_n^2 at each height. C_n^2 (32 m) and possibly C_n^2 (16 m) may be in the mixed boundary layer above the free convection layer if the inversion base 1 h after sunrise on this day and location is similar to that reported for a typical day at a Minnesota location 1 h after sunrise [12].

In the evening transition periods, the 290PM measurements showed slow, monotonic variation in C_n^2 at heights of 8 and 32 m. In contrast to the other two test periods, the 289PM period was dynamic and displayed a complicated C_n^2 behavior. Figure 2 plots the raw data with 10-s averages, and Fig. 5 plots the 5-min moving average processed data. C_n^2 minima are clearly seen at 4 and 8 m at the expected time after sunset. C_n^2 (16, 32 m) is relatively unaffected by surface effects during the transition period. After the time of the C_n^2 minima, C_n^2 at 8 and 16 m increases, while C_n^2 at 32 m decreases to unusually low levels ($<10^{-16}$ $m^{-2/3}$) with the result that the sensitivity of the sensor may be a limiting factor.

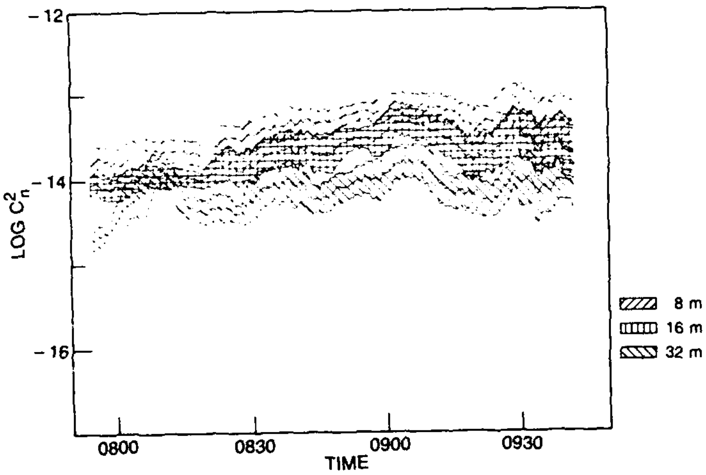

Fig. 4 — Plot of 5-min moving average of log C_n^2 $(m^{-2/3})$ during 289AM

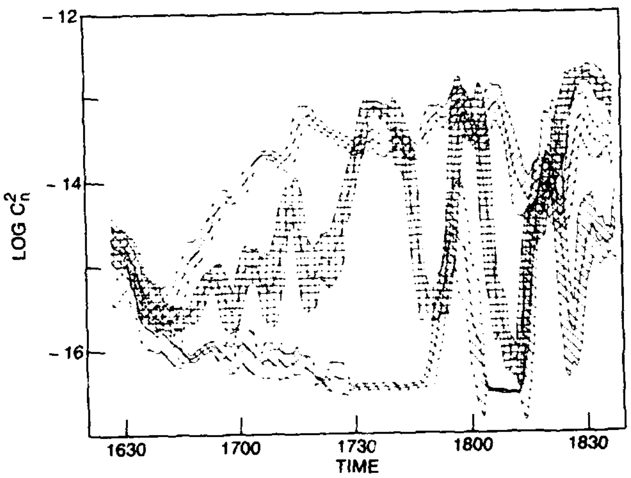

Fig. 5 — Plot of 5-min moving average of log C_n^2 $(m^{-2/3})$ during 289PM

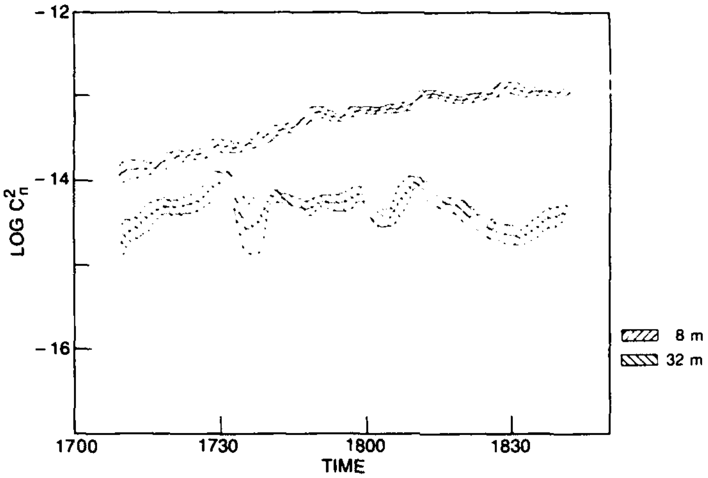

Fig. 6 — Plot of 5-min moving average of log C_n^2 $(m^{-2/3})$ during 290PM

Approximately 40 min after the C_n^2 (4, 8 m) minima, C_n^2 (16 m) began an erratic behavior with C_n^2 (32 m) following about 10 min later. The cause of this behavior is unknown. However, we note that drainage flows occur in this area because of the proximity to the San Andres mountains, and that even under nearly ideal conditions drainage flows influence the nocturnal boundary layer evolution [15]. The degree of influence depends on slope, wind speed, and wind direction.

To examine the scaling of C_n^2 with height, we plotted log C_n^2 vs log height at 1-min intervals with each height containing 7 datapoints, each of which averaged 10 s. Figure 7 presents examples of this. Inspection of the more than 200 computer-generated plots indicates that C_n^2 (4 m) and C_n^2 (8 m) were of a similar order of magnitude, but at 8 m and above, C_n^2 rapidly decreased with height.

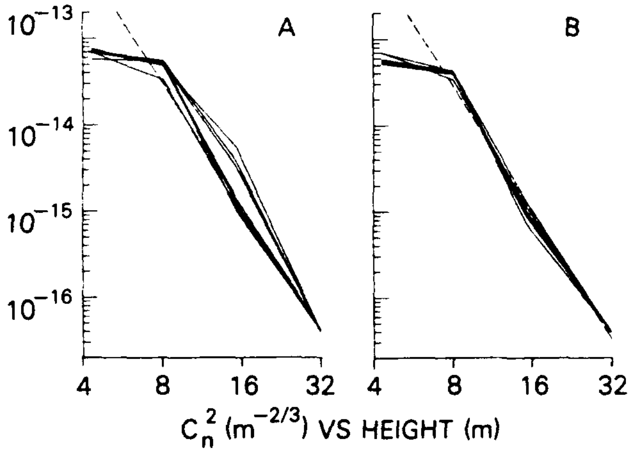

Fig. 7 — 289PM, C_n^2 at times 17:20:30 (A) and 17:21:30 (B). Each of the seven broken lines on each plot connects one 10-s interval. The dashed line slope (A) is −5.2 and (B) is −[illegible] with 1 m intercepts of 2.4E-9 and 1.0E-9, respectively.

To scale the data at 8, 16, and 32 m, a power law was assumed:

$$C_n^2 = (C_n^2)_0 \, (z/z_0)^m \tag{3}$$

where $(C_n^2)_0$ and m are constants to be determined and z_0 is equal to 1 m. This form is correct for the free convection layer with m = -4/3 during unstable (daytime) conditions and m = -2/3 during stable (nighttime) conditions [2]. The -4/3 law has been validated at heights of up to 500 m [16] and beyond [17] under fully developed convective conditions.

Table 2 lists the results of the least-squares fit to Eq. (2) for periods that sampled 5 and 15 min of data. The uncertainty in the fitted parameters was calculated from standard formulas [18]. The time presented is the mean time so that the first row is 8:00 ± 2.5 min for the 5 min averaging period and 8:00 ± 7.5 min for the 15 min averaging period. The shorter period contains 30 10-s moving average datapoints at each height while the longer period has 90 datapoints at each height. The similarity of the 5- and 15-min average suggests that these periods are reasonable.

Table 2 — Least-Squares Parameters and Standard Errors Based on the Fit of 8-, 16-, and 32-m height C_n^2 Data to Eq. (2)

		5-min average (e.g., from 7:57.30 to 8:02.30)				15-min average (e.g., from 7:52.30 to 8:07.30)			
	Mean Time	$(C_n^2)_0$	x ÷	m	±	$(C_n^2)_0$	x ÷	m	±
	8:00	2.2E-13	1.2	−1.21	0.08	2.3E-13	1.2	−1.20	0.05
	8:15	2.0E-13	1.2	−1.00	0.06	1.3E-13	1.1	−0.84	0.05
289AM	8:30	5.9E-13	1.3	−1.32	0.09	5.5E-13	1.2	−1.28	0.05
	8:45	1.2E-12	1.2	−1.51	0.07	8.9E-13	1.1	−1.36	0.05
	9:00	9.5E-13	1.3	−1.24	0.09	1.0E-12	1.1	−1.25	0.05
	9:15	2.0E-12	1.3	−1.60	0.08	1.1E-12	1.2	−1.37	0.06
	9:30	2.4E-12	1.3	−1.54	0.09	1.3E-12	1.2	−1.46	0.07
	16:45	1.4E-14	1.2	−1.46	0.08	1.3E-14	1.2	−1.37	0.07
	17:00	3.1E-12	1.4	−3.0	0.1	7.5E-12	1.2	−3.32	0.07
	17:15	3.4E-10	1.6	−4.4	0.2	3.6E-10	1.3	−4.51	0.09
289PM	17:30	1.0E-09	2.0	−4.7	0.2	1.4E-09	1.6	−4.8	0.2
	17:45	6.5E-10	2.0	−4.7	0.2	8.0E-10	1.6	−4.7	0.2
	18:00	2.5E-10	2.3	−3.6	0.3	1.9E-10	1.8	−3.8	0.2
	18:15	5.8E-13	2.5	−2.3	0.3	9.3E-13	2.0	−2.1	0.2
	18:30	2.9E-11	2.4	−2.6	0.3	4.7E-12	1.8	−2.1	0.2
	17:15	9.7E-14	1.2	−0.97	0.06	1.3E-13	1.1	−1.09	0.05
	17:30	1.2E-13	1.2	−0.76	0.05	2.0E-13	1.2	−1.06	0.05
290PM	17:45	9.6E-13	1.1	−1.52	0.04	1.1E-12	1.1	−1.55	0.03
	18:00	2.2E-12	1.1	−1.69	0.04	2.8E-12	1.1	−1.84	0.03
	18:15	7.2E-12	1.1	−2.07	0.03	4.8E-12	1.1	−1.94	0.03
	18:30	4.6E-11	1.1	−2.90	0.03	3.0E-11	1.1	−2.73	0.02

A simple test was performed to check the assumption that Eq. (3) with its fitted parameters gave an adequate representation of the data. Average log C_n^2 and its standard deviation were calculated at each height for each time interval. This resulted in a range for C_n^2 containing 67% of

the data. A test was then made to determine if calculated C_n^2 from Eq. (3) fell within this range. The test showed that calculated C_n^2 was within the experimental range for all heights and intervals except the following during 289PM: 17:30, 5- and 15-min intervals; 17:45, 5-min interval; 18:00, 5-min interval; and 18:30, 5- and 15- min intervals.

During 289AM, *m* was, in general, almost equal to -4/3 within experimental error for the 15-min averaging period. No time-dependent trend is apparent in the slope parameter. Averaging over 5 or 15 min does not markedly effect the values for the fitted parameters, and little difference exists between successive 15-min intervals.

The C_n^2 height dependence during 289PM was much more complicated. In the first 15-min interval, the air-surface temperature difference moved from positive to negative. C_n^2 values at all heights dropped rapidly, and C_n^2 values at 8 and 16 m approached their expected minima. C_n^2 at all heights appears to be correlated, and *m* is close to -4/3. In the next 15-min, C_n^2 at 8 m began to rebound to high levels; C_n^2 at 16 m was relatively constant; and C_n^2 at 32 m drifted to levels below 10^{-16} $m^{-2/3}$ and may have reached the minimum detectable level. The trends continued through the third 15-min time interval and well into the fourth. In the last hour of 289PM, C_n^2 at 16 and 32 m changed erratically.

During all but the first 15 min, *m* values ranged from -2.3 to -4.8. If the 32 m sensor was limited by its sensitivity, the actual *m* values would be more extreme. No explanation can be provided for these values except that these field conditions are far from ideal. The dissolution of the convective boundary layer has been reported to be rather abrupt [12] and the evening/night stable boundary layer has been reported to evolve rapidly [15]. Drainage can strongly affect turbulence levels [15]. The fitted parameters under these conditions should be considered only as a means to extrapolate C_n^2 at a particular time and location, with an assumption about the validity of Eq. (2). The frequency of occurrence of the anomalous *m* values at this site is unknown, but a report [19] on atmospheric conditions in the area from 22 March to 14 April 1978 cites a number of evening/night periods in which $m < -2$ for periods of 30 min to 3 h.

Fortunately, the second evening test period was not so complicated. Nevertheless, it was flawed by the inoperability of the 16 m sensor. Figure 3 presents a sample of the data taken during the time the aircraft-mounted probe was flown along a slant angle path that began near the sensor tower and followed the path of our laser propagation line of sight toward the San Andres foothills. The flight segment of interest occurred from 18:38:03 to 18:40:26. The sensor data is plotted as the average of the 15 10-s datapoints in the interval 18:38:00 to 18:40:30. These points and associated standard deviation are: 4.5 ± 0.4E-14 (4 m), 9.1 ± 1.0E-14 (8 m), and 3.7 ± 0.7E-15 (32 m) $m^{-2/3}$. The line drawn through the sensor data was obtained from a least-squares fit to the 15 points at 8 and 32 m. The data were recorded after the last complete 15-min period listed in Table 2. The slope through the 8 and 32 m heights is -2.3 and can be compared to a similar value at 18:00 ± 7.5 min. With allowance for calibration errors, agreement between the aircraft and tower data is satisfactory. The agreement between the extrapolated sensor data and plane data at >32 m supports the assumption that Eq. (2) is acceptable to heights of about 90 m above the desert floor. The plane data is relevant to our laser propagation test because the flight followed the 10.5 km path from the sensor/transmitter site to a point near the receiver site located in the San Andres foothills.

SUMMARY

C_n^2 measurements at two or three heights were least-squares fit to a power law. Averaging periods of 5 and 15 min gave similar results. The fitted parameters and C_n^2 measurements can be ranked in terms of quality from best to worst:

1. 289AM data were well-behaved. The slope of the power law was close to -4/3 expected for free convection. Extrapolation to 88 m has an uncertainty because the free convection layer is not expected to extend to 88 m, and the mixed boundary layer above the free convection layer may have a different height dependence. Accurate extrapolation, however, is not important for r_0.

2. 290PM data were well-behaved, but data were recorded at only two heights rather than the usual three heights. The power law slope ranged from about -2/3 to -4/3 except for the last 15 min. Comparison of flight data to the power law extrapolation showed reasonable agreement. The flight occurred near the end of 290PM.

3. 289PM data were complicated. The first 15 min were well-behaved. In the next hour, the trends in C_n^2 at each height were smooth. However, the power law slope was anomalous ($m < -4/3$). The last hour was marked by rapid oscillations in C_n^2, making this data of uncertain value.

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